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TECHNICAL NOTE

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PERFORMANCE EVALUATION OF FIXED- AND VARIABLE-AREA ROCKET EXHAUST DIFFUSERS USING SINGLE AND CLUSTERED NOZZLES WITH AND WITHOUT GIMBALING

By Bruce E. Church, William L. Jones,
and Richard J. Quentmeyer

Lewis Research Center
Cleveland, Ohio

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PERFORMANCE EVALUATION OF FIXED- AND VARIABLE-AREA ROCKET EXHAUST DIFFUSERS USING SINGLE AND CLUSTERED NOZZLES WITH AND WITHOUT GIMBALING

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SUMMARY

An investigation of exhaust diffusers used for altitude simulation in testing rocket engines was conducted with model diffusers and gaseous nitrogen as the working fluid. This investigation was conducted to evaluate the effects on performance of gimbaling clustered nozzles in a single fixed-area exhaust diffuser. A two-nozzle cluster was gimbaled in all attitudes in four different exhaust-diffuser configurations: (1) a straight circular tube, (2) a straight figure-eight tube, (3) a circular tube with a second throat, and (4) a figure-eight tube with a second throat.

Gimbaling clustered nozzles had little effect on the operating pressure ratio for either straight-tube or second-throat diffusers, but caused a large increase in the starting-pressure-ratio requirements in some straight-tube exhaust diffusers. The performance of two or four clustered nozzles with no gimbaling was compared with single-nozzle performance on the basis of the ratio of diffuser area to nozzle-throat area. The performance was found to be dependent on the diffuser- to nozzle-throat-area ratio and independent of both the number of primary nozzles and the nozzle-area ratio.

A separate investigation was also conducted to evaluate the performance improvement obtainable with a variable-area exhaust diffuser. This type of diffuser achieved a 26-percent reduction in starting pressure ratio, a 40-percent reduction in operating pressure ratio, and a 50-percent reduction in the overall diffuser length over the values attainable with a fixed-area second-throat diffuser.

INTRODUCTION

Rocket propulsion systems designed for operation in the upper atmosphere or in space utilize nozzles with large expansion-area ratios to obtain high specific impulse. In order to evaluate the performance of these nozzles in a ground test installation, some means of reducing nozzle back pressure and allowing full nozzle flow must be provided. Altitude facilities that employ either mechanical exhausters or auxiliary powered ejectors are often used for this purpose, but these facilities are limited by their physical capabilities for handling large engines and present problems in cooling and exhaust disposition. Another device for altitude simulation, which is currently utilized for testing single-rocket engines, is the exhaust diffuser, sometimes called a zero-flow ejector. Several studies of these exhaust diffusers have been conducted, and the results are reported in references 1 to 6.

The current trend toward gimbaled multiple engines in space-vehicle propulsion systems gives rise to a need for altitude-performance evaluations of these engine configurations. Exhaust diffusers of increased flexibility and capability are needed to handle these propulsion systems. The effects of single-nozzle gimbaling on exhaust-diffuser performance are reported in references 1 and 2, and a brief investigation of exhaust-diffuser performance with clustered nozzles is described in reference 3. Since the combined effects of gimbaling and clustering on diffuser performance have not been studied, an investigation was undertaken to study these effects in several exhaust-diffuser configurations. Yaw, pitch, and roll attitudes were studied with both straight-tube and second-throat exhaust diffusers. With gaseous nitrogen as the working fluid, data were obtained for 15° conical nozzles with area ratios of 25 and 40 over a range of chamber- to ambient-pressure ratios of 30.0 to 120.0.

As a part of a continuing program to improve performance of exhaust diffusers, a separate investigation was conducted. It has been previously reported (ref. 5) that second-throat exhaust diffusers can have a substantial improvement in performance over straight-tube exhaust diffusers. Theoretically, if the second-throat area is reduced after the diffuser is started, the diffuser is able to operate at a much lower overall pressure ratio. Consequently, it was the purpose of this second investigation to determine the performance improvement that could be obtained by utilizing a variable-area second-throat exhaust diffuser. A translating internal spike was employed for this investigation; the spike provided a variable-flow area and had an overall length that was shorter than the conventional fixed-geometry diffuser. Data were obtained with a 15° conical nozzle having an area ratio of 25. Gaseous nitrogen was used in the performance evaluation of single- and two-step spikes over a range of spike semivertex angles of 8° to 30° with chamber- to ambient-pressure ratios up to 30.0.

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SYMBOLS

A	cross-sectional area
A_d/A_*	diffuser- to nozzle-throat-area ratio
D	maximum diameter
d	minimum diameter
L	overall diffuser length
l	length
P	total pressure
P_c/P_0	chamber- to ambient-total-pressure ratio
p	static pressure
r	spike-tip radius
s	spacing between nozzle exit plane and plane of shell divergence
z	spike-tip displacement from nozzle throat
β	gimbal angle
δ	contraction angle
ϵ	nozzle-area ratio, A_n/A_*
θ	subsonic diffuser angle
λ	shell divergence angle
σ	spike-tip semivertex angle
φ	spike-base semivertex angle for two-step spikes
ψ	contraction ratio, A_d/A_t

Subscripts:

c	chamber
d	diffuser

e	diffuser exit
n	nozzle exit
s	spike tip
t	second throat
0	ambient
*	nozzle throat (for single-nozzle configurations) or sum of nozzle throats (for multiple-nozzle configurations)

APPARATUS

Clustered-Nozzle Investigation

The test apparatus for the clustered-nozzle investigation (figs. 1 and 2) consisted of a chamber, a nozzle cluster, and an exhaust diffuser, which discharged to the atmosphere. Provisions were made for changing the number and the orientation of the nozzles as well as the exhaust-diffuser configuration.

The four exhaust diffusers investigated were a straight circular tube, a circular tube with a second throat, a figure-eight tube with a second throat, and a straight figure-eight tube (fig. 2).

Groups of two and four 15° conical nozzles with area ratios of 25 and 40 were studied over a range of gimbal angles of 0° to 7° in the yaw, pitch, and roll attitudes (fig. 3). All nozzles had throat diameters of 0.185 inch.

The clustered-nozzle configurations investigated and their characteristics are listed in table I.

Variable-Area-Exhaust-Diffuser Investigation

The test apparatus, (figs. 4 and 5), consisted of a chamber and a nozzle, to which a series of exhaust-diffuser configurations could be attached. Provisions were made for changing the nozzle, the spacing, the shell, and the spike. The flow area of the exhaust diffuser was varied by means of a remotely positioned internal spike. An electrical actuator (fig. 5) was used to provide the spike translation. The

diffuser was operated with a 15° conical nozzle having an area ratio of 25 and a throat diameter of 0.26 inch. All configurations had a diffuser- to nozzle-throat-area ratio of 35.4.

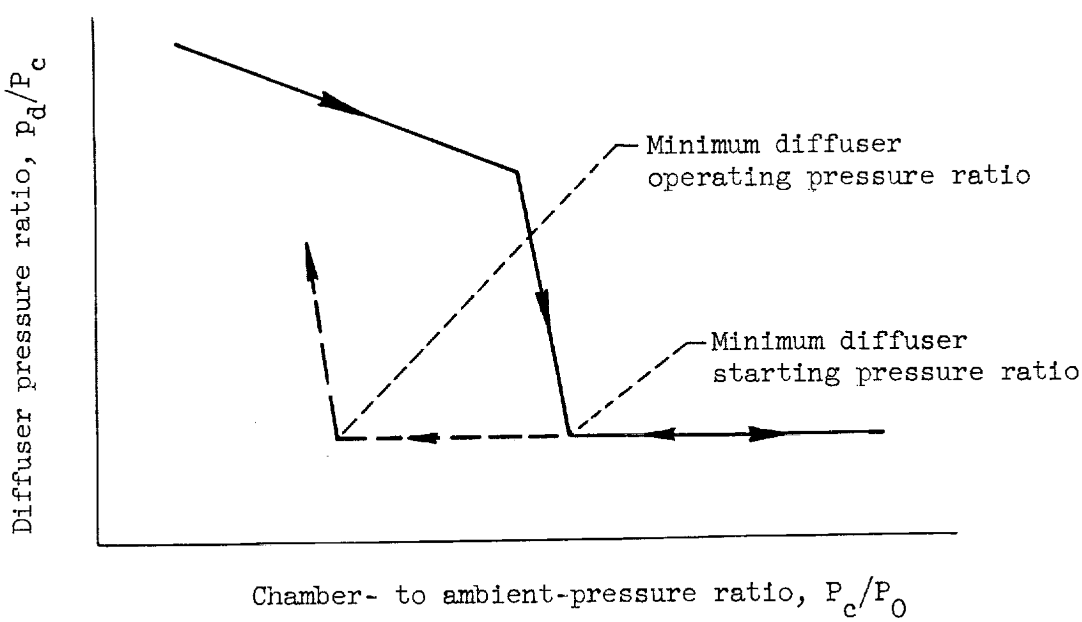
A list of the variable-area-exhaust-diffuser configurations and their characteristics is given in table II.

Instrumentation

The primary pressure measurements were inlet total pressure P_c and diffuser static pressure p_d; these measurements were taken at the points shown in figure 1(a). For the variable-area diffuser, additional static pressures were measured at the nozzle exit and along the diffuser wall. A Bourdon-type gage was used to measure the inlet pressure, and all static pressures were recorded in photographs of a gage and manometer system. A mercury barometer was used to determine the ambient or atmospheric pressure.

PROCEDURE

Fixed-area-exhaust-diffuser performance data were obtained by slowly increasing the chamber pressure (thereby increasing the chamber- to ambient-pressure ratio) until a minimum diffuser pressure ratio was obtained as illustrated in the following sketch:



The chamber- to ambient-pressure ratio corresponding to this minimum diffuser pressure ratio is termed the minimum diffuser starting pressure ratio. Any further increase in the chamber- to ambient-pressure ratio had no effect on the diffuser pressure ratio. In many cases once the diffuser was "started," the chamber- to ambient-pressure ratio could be reduced to a value below the minimum starting pressure ratio without affecting the diffuser pressure ratio. This hysteresis was pronounced in many cases. The lowest value to which the chamber- to ambient-pressure ratio could be reduced without affecting the diffuser pressure ratio is termed the minimum diffuser operating pressure ratio. Any further reduction in chamber- to ambient-pressure ratio resulted in a sudden increase in the diffuser pressure ratio.

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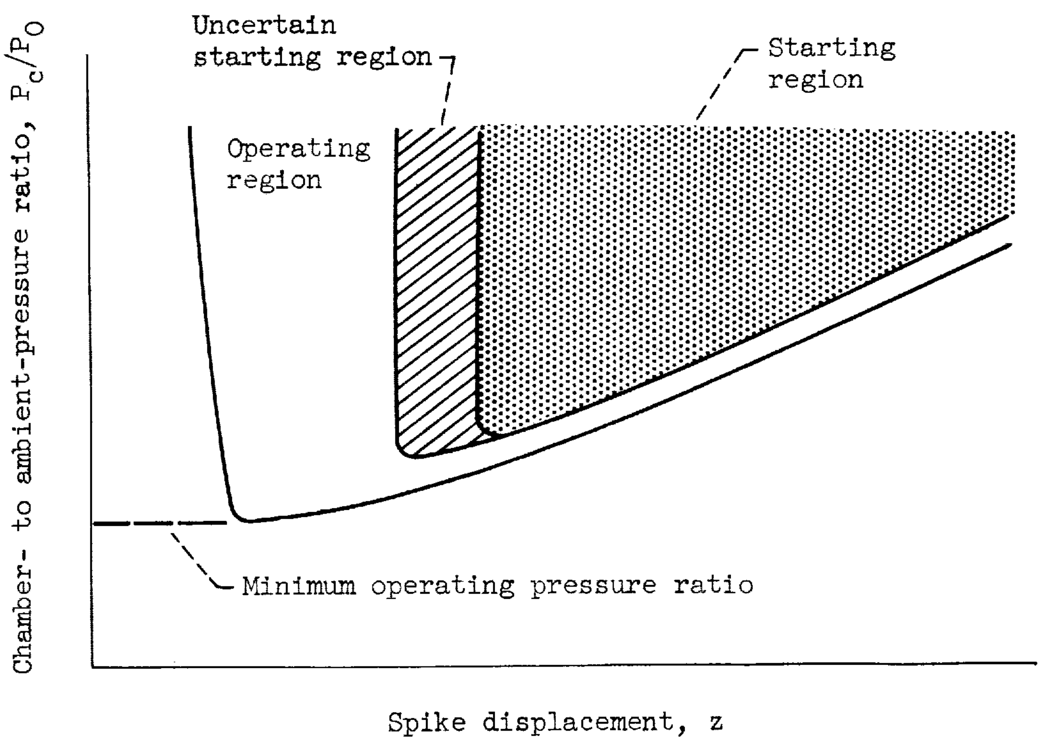
The variable-area exhaust diffuser could be "started" in two ways: by proper positioning of the spike and then increasing the chamber pressure (increasing chamber- to ambient-pressure ratio), or by varying the spike displacement (i.e., the contraction ratio) at constant chamber- to ambient-pressure ratio as shown in the following sketch:



Variation of the spike displacement in either direction could also cause a sudden increase in the diffuser pressure ratio, which indicates that the diffuser is no longer operating. The minimum operating pressure ratio was obtained by varying both the chamber- to ambient-pressure ratio and the spike displacement. Performance maps were obtained with various spacings s, and from these the optimum spacing for each spike and shell combination was determined.

RESULTS AND DISCUSSION

Gimbaled Clustered Nozzles

The effect of nozzle gimbal angle on the performance of the various exhaust diffusers is presented in figure 6. The straight-circular-tube exhaust diffuser (fig. 6(a)) was designed to accomodate four nozzles that were not gimbaled or two 25-area-ratio nozzles that were gimbaled up to 7°. Data are presented for two conical nozzles with gimbal angles up to 5° in the yaw and pitch attitudes and up to 7° in the roll attitude. Also shown are data points for two nozzles with area ratios of 40 and four nozzles with area ratios of 25 with no gimbaling.

The two 25-area-ratio nozzles with no gimbaling required a chamber-to ambient-pressure ratio of 93.0 for starting; no hysteresis was observed. Gimbaling in the yaw and pitch attitudes resulted in an increase in the minimum starting pressure ratio with a large amount of hysteresis; whereas, gimbaling up to 7° in the roll attitude had little effect on performance. These high starting-pressure-ratio requirements at large gimbal angles could be avoided by starting the exhaust diffuser with the nozzles in a nongimbaled attitude and then gimbaling the nozzles.

Comparison of the starting pressure ratios for the nozzles with area ratios of 25 and 40 indicates no change in starting pressure ratio as a result of a change in nozzle-area ratio. Increasing the number of nozzles from two to four (reducing the diffuser- to nozzle-throat-area ratio by 50 percent) lowered the minimum starting pressure from 93.0 to 48.0. This reduction in starting pressure ratio as a function of diffuser- to nozzle-throat-area ratio agrees with the results reported in references 1 to 6. Physical limitations of the exhaust diffuser made it impossible to gimbal either the two 40-area-ratio nozzles or the four 25-area-ratio nozzles.

The effect of gimbal angle on the performance of the straight figure-eight tube is presented in figure 6(b). This diffuser was designed to minimize the diffuser- to nozzle-throat-area ratio and still permit gimbaling with a two-nozzle cluster. Data are presented for gimbal angles up to 7° in the yaw and roll attitudes and up to 5° in the pitch attitude for two conical nozzles with area ratios of 25. With no gimbaling, this reduction in diffuser- to nozzle-throat-area ratio resulted in a reduction in starting chamber- to ambient-total-pressure ratio from 93.0 for the straight circular tube to 65.5 for the straight figure-eight tube. When the nozzles were gimbaled in the yaw and roll attitudes, the minimum starting and operating pressure ratios increased with no hysteresis. In the pitch attitude, however, a sharp increase in starting chamber- to ambient-total-pressure ratio was observed along with a large amount of hysteresis. These effects were possibly results of interaction between the shock system and the sharp longitudinal edges of the figure-eight tube.

The effect of gimbal angle on the performance of a circular-tube second-throat exhaust diffuser is shown in figure 6(c). Data are given for two 25-area-ratio nozzles with gimbal angles up to 5° in the yaw attitude and up to 7° in the pitch and roll attitudes. Data are also presented for clusters of two nozzles and four nozzles of area ratios of 10 and 25, respectively.

An improvement in starting pressure ratio from an estimated 115.0 for a straight circular tube to 61.0 for the circular-tube second-throat diffuser both with the same diffuser- to nozzle-throat-area ratio, was observed for two nozzles having area ratios of 25 with no gimbaling. Gimbaling these nozzles in any attitude had very little effect on performance. Varying the nozzle-area ratio and the number of nozzles had an effect on performance similar to that shown in figure 6(a); that is, changing the nozzle-area ratio had no effect on starting pressure ratio, and doubling the number of primary nozzles decreased the starting pressure ratio from 61.0 for two nozzles to 30.0 for four nozzles.

The effect of gimbal angle on the performance of a figure-eight-tube second-throat exhaust diffuser is presented in figure 6(d). This diffuser was designed to reduce the diffuser- to nozzle-throat-area ratio A_d/A_* for a two-nozzle cluster and to utilize the inherent performance improvement of a second-throat diffuser. The diffuser had a figure-eight straight section surrounding the nozzles, a figure-eight contraction into a circular second throat, and a conical subsonic diffuser. Data are presented for two conical nozzles with an area ratio of 25 at gimbal angles up to 7° in the yaw, pitch, and roll attitudes. The minimum starting pressure ratio of 41.4 for a zero gimbal angle is comparable with 65.0 for the straight figure-eight tube and 61.0 for the second-throat circular tube. Increasing the gimbal angle in any attitude resulted in only minor changes in the starting and operating pressure ratio; no hysteresis was observed.

In general, gimbaling clustered nozzles had little effect on operating performance for either the straight-tube or the second-throat exhaust diffusers. An increase in the starting-pressure-ratio requirements, however, was observed for some of the straight-tube-exhaust-diffuser configurations.

The results of the investigation of clustered nozzles with no gimbaling are presented in figure 7 and curves are presented not only for experimental data for two- and four-nozzle clusters for all four exhaust diffusers but also for the single-nozzle straight-tube and second-throat exhaust diffusers of reference 5. Theoretical operating lines for straight-tube and second-throat exhaust diffusers are also shown. The straight-tube theoretical line was calculated from one-dimensional normal-shock theory, and the second-throat theoretical line was calculated by means of one-dimensional theory in conjunction with the

Kantrowitz contraction ratio. Close agreement between the experimental data of the present investigation and the data of reference 5 indicates that diffuser performance is dependent on the diffuser- to nozzle-throat-area ratio A_d/A_* as well as the type of diffuser (i.e., straight tube or with second throat). The data also indicate that performance is not affected by the number of primary nozzles or the nozzle-area ratio.

Variable-Area Exhaust Diffuser

It has been previously mentioned that the variable-area exhaust diffuser could be started by varying either chamber pressure (hence, P_c/P_0) or spike displacement (hence, ψ). Another variable that affected diffuser performance was spacing s. Performance maps were constructed to determine what spacing resulted in optimum performance for each spike and shell combination. All data presented herein were obtained with optimum diffuser spacing.

The effect of shell divergence angle on the performance of 15° spike configurations is presented in figure 8. When the divergence of the spike and shell formed a constant-flow area along the flow passage, a minimum operation pressure ratio of 9.2 was obtained. The minimum starting pressure ratio for this configuration was 15.2. The minimum starting and operating pressure ratios of the 24° spike also occurred with the constant-flow-area configuration.

The effect of spike semivertex angle on the performance of the concentric and constant-flow-area configurations is presented in figure 9. Despite the fact that the 8° spike and shell combination could not be started within the pressure limitations of this investigation, spikes were evaluated over a range of semivertex angles of 8° to 30°. In general, the constant-flow-area configurations resulted in lower starting and operating pressure ratios than the concentric configurations regardless of spike semivertex angle. The lowest operating pressure ratio, 9.2, was obtained when the 15° spike was used in the constant-flow-area-configuration, and the lowest starting pressure ratio, 11.3, was obtained when the 24° spike was used in the constant-flow-area configuration.

The effect of spike-tip radius on diffuser performance is presented in figure 10 for the 15° spike in the constant-flow-area configuration. Both the starting and operating pressure ratios increase rapidly with an increase in spike-tip radius; therefore, in order to utilize the performance improvement gained through the use of this type of diffuser, it is essential that the spike tip be as sharp as possible.

In addition to single-step spikes, two-step spikes were investigated (table II(b)) to determine whether performance improvement could be

realized because of the possibility of a more efficient internal shock system. The parameters studied included the spike-tip semivertex angle σ, the spike-base semivertex angle φ, and the spike-tip length l_s.

The effect of spike-tip length on diffuser performance is presented in figure 11. In general, the data illustrate that as the spike-tip length was increased the operating pressure ratio improved. This improvement, however, was achieved at the expense of a sharp increase in starting pressure ratio. Data for the single-step spike indicate better starting characteristics with approximately the same operating performance. Within the scope of this investigation, therefore, the two-step spike did not achieve an overall performance improvement greater than that of the single-step spike.

The performance achieved by various types of exhaust diffusers is presented in figure 12. Both the experimental data for three variable-area configurations and the data for the straight-tube and second-throat diffusers are presented. With the 24° spike constant-flow-area configuration, a minimum starting pressure ratio of 11.3 was achieved; this ratio is approximately 26 percent lower than that of the fixed-geometry second-throat exhaust diffuser. With the same spike configuration a minimum operating pressure ratio of 9.7 was achieved; this ratio is approximately 37 percent lower than that of the second-throat exhaust diffuser. An even greater improvement in operating performance was achieved when the 15° spike constant-flow-area configuration was used. With this configuration an operating pressure ratio of 9.2 was achieved, which is approximately 40 percent lower than that of the second-throat exhaust diffuser.

In addition to the performance improvement, the variable-area exhaust diffuser offers a considerable reduction in overall length. A comparison of the overall diffuser length of various types of exhaust diffusers is presented in figure 13. A reduction of approximately 50 percent in the length of the fixed-geometry diffusers was obtained when the spike-type variable-area diffuser was used.

There are, however, additional problem areas that are outside the scope of this investigation; these must be investigated before this type of diffuser can be used with full-scale rocket engines. Some of these problems include: the cooling of the internal spike, the complications incurred when large electrical or hydraulic actuators are used to move the spike, and the possible ducting or removal of toxic exhaust gases.

SUMMARY OF RESULTS

An investigation of model rocket exhaust diffusers was conducted to determine what effects gimbaling clustered nozzles has on the performance of various fixed-geometry exhaust diffusers. Another investigation

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was conducted to determine the performance improvement possible with a spike-type variable-area exhaust diffuser. From these investigations, the following results were obtained:

1. Gimbaling clustered nozzles had little effect on the operating pressure ratio for either the straight-tube or the second-throat exhaust diffusers.

2. Gimbaling clustered nozzles caused a large increase in minimum starting-pressure-ratio requirements in some straight-tube exhaust diffusers but had little effect in second-throat exhaust diffusers.

3. The performance of two- or four-clustered nozzles with no gimbaling was compared with single-nozzle performance on the basis of the ratio of diffuser area to the sum of the nozzle-throat areas, and diffuser performance was found to be independent of the number of nozzles and the nozzle-area ratio.

4. A variable-area exhaust diffuser that used a 24° internal spike with a constant-flow area achieved a 26-percent lower starting pressure ratio and a 37 percent lower operating pressure ratio than was previously possible with a fixed-area second-throat exhaust diffuser.

5. A variable-area exhaust diffuser that used a 15° internal spike with a constant-flow area achieved a 40 percent lower operating pressure ratio than was previously possible with a fixed-area second-throat exhaust diffuser.

6. A reduction of 50 percent in overall diffuser length of a fixed-geometry second-throat exhaust diffuser was possible when a spike-type variable-area exhaust diffuser was used.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, April 20, 1962

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TABLE I. - CLUSTERED-NOZZLE-EXHAUST-DIFFUSER CONFIGURATIONS;

15° CONICAL NOZZLES

(a) Straight-tube exhaust diffusers without subsonic diffuser

Exhaust diffuser	Diffuser-to nozzle-throat-area ratio, A_d/A_*	Diffuser overall length-diameter ratio, L/D_d	Number of nozzles	Nozzle-area ratio, ϵ	Gimbal angle, β, deg		
					Yaw	Pitch	Roll
Straight circular tube	123.0	8.3	2	25	0,3,5	3,5	3,5,7
	61.5	8.3	4	25	0	---	-----
	123.0	8.3	2	40	0	---	-----
Straight figure-eight tube	87.0	[a]11.7	2	25	0,3,5,7	3,5	3,5,7

(b) Second-throat exhaust diffusers with subsonic diffuser. Diffuser-exit- to second-throat-area ratio, 2.0; subsonic diffuser angle, 8°; contraction angle, 6°

Exhaust diffuser	Diffuser-to nozzle-throat-area ratio, A_d/A_*	Contraction ratio, ψ	s/D_d	l_t/d_t	Number of nozzles	Nozzle-area ratio, ϵ	Gimbal angle, β, deg		
							Yaw	Pitch	Roll
Circular tube second throat	155.0	2.06	0.34	6.42	2	25	0,3,5,7	3,5,7	3,5,7
	77.5	2.06	.34	6.42	4	25	0	-----	-----
	155.0	2.06	.20	6.42	2	40	0,5	5	5
Figure-eight tube second throat	87.0	1.94	[a]0.54	6.42	2	25	0,3,5,7	3,5,7	3,5,7

[a]Based on equivalent $D_d = 2\left(\frac{\text{cross-sectional area}}{\text{perimeter}}\right)$.

TABLE II. - VARIABLE-AREA-EXHAUST-DIFFUSER CONFIGURATIONS

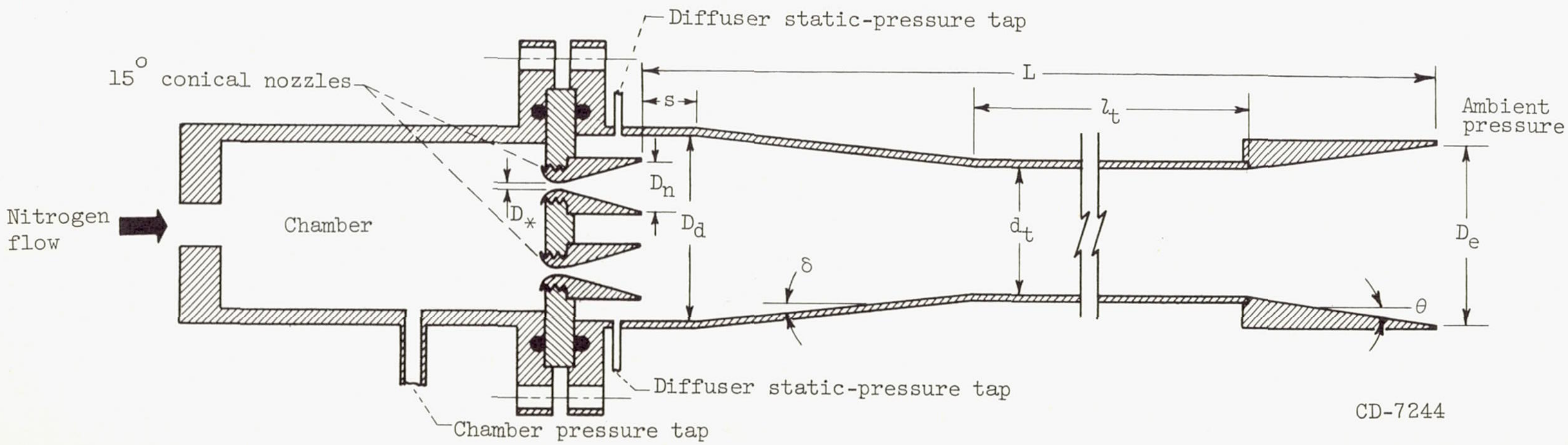
[15° conical nozzle; nozzle-area ratio, 25; diffuser-to nozzle-throat-area ratio, 35.4.]

(a) Single-step spike

Spike-tip semivertex angle, σ, deg	Shell divergence angle, λ		Spike-tip radius, r, in,	Spacing between nozzle exit plane and plane of shell divergence, s, in.	Remarks
	deg	min			
8	8	--	-		Could not start
12	10	50	-	2.17 - 4.07	Constant-flow area between spike and shell
↓	12	--	-	3.04 - 3.67	Concentric spike and shell
15	10	50	-	1.14 - 2.49	- -
	12	--	-	1.54 - 2.17	- -
	13	20	-	1.85 - 2.49	Constant-flow area between spike and shell
	15	--	-	1.85 - 2.89	Concentric spike and shell
↓	21	30	-	1.85 - 2.21	- -
24	15	--	-	1.14 - 1.81	- -
	21	30	-	0.44 - 1.54	Constant-flow area between spike and shell
	24	--	-	1.14 - 1.85	Concentric spike and shell
↓	27	25	-	1.14 - 1.81	- -
30	27	25	-	0.76 - 1.85	Constant-flow area between spike and shell
↓	30	--	-	1.14 - 1.85	Concentric spike and shell
15	13	20	0.125	1.81 - 3.57	
			.250	2.64 - 3.57	Constant-flow area between spike and shell
↓	↓	↓	.375	2.57 - 3.25	

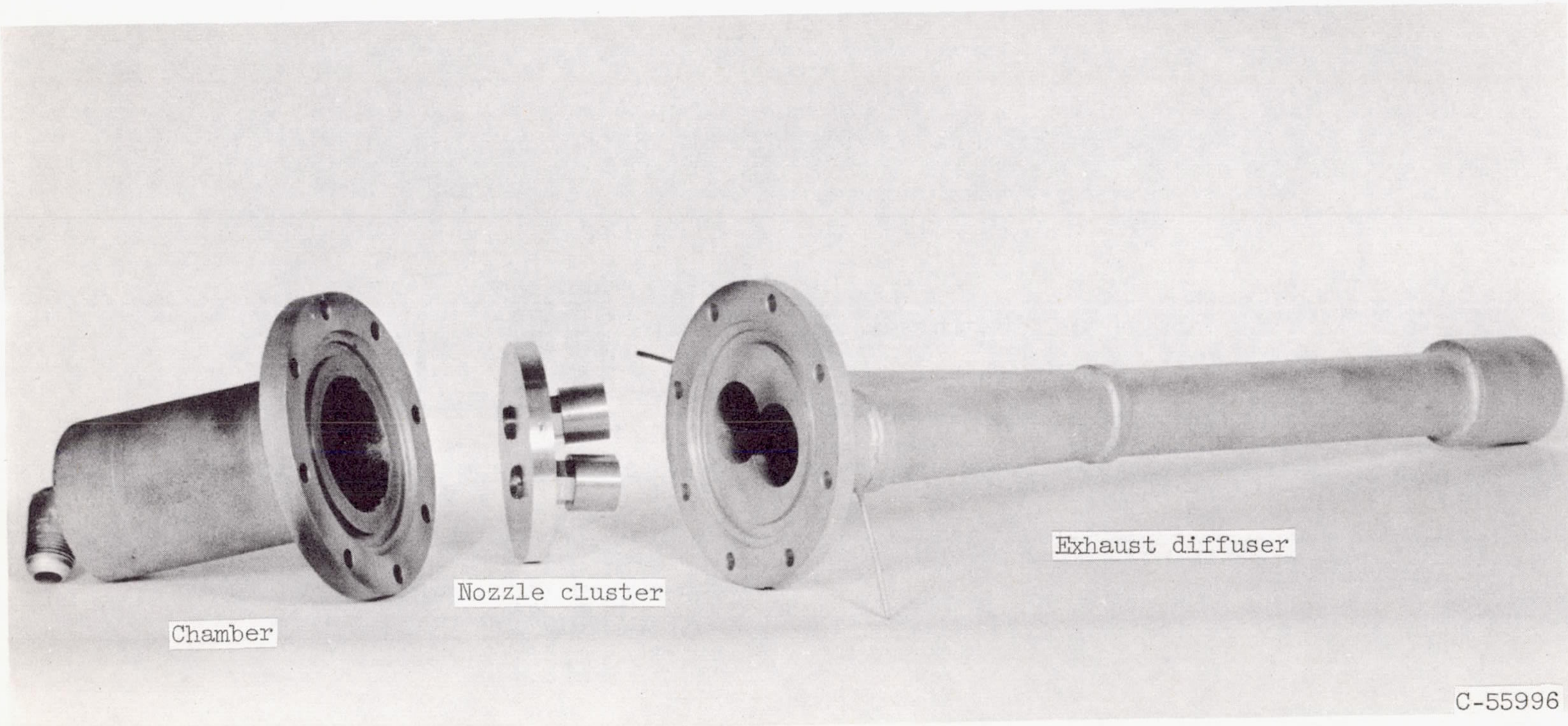
(b) Two-step spike

Spike-tip semivertex angle, σ, deg	Spike-base semivertex angle for two-step spikes, φ, deg	Shell divergence angle, λ		Length, l, in.	Spacing between nozzle exit plane and plane of shell divergence, s, in.	Remarks
		deg	min			
8	15	13	20	3.452	2.17 - 2.85	
				3.750	2.21 - 2.85	Constant-flow area between spike and shell
				4.000	2.21 - 2.85	
	30	27	25	3.452	2.17 - 2.85	Constant-flow area between spike and shell
		30	--	3.452	2.17 - 2.85	Concentric spike and shell
				3.750	2.49 - 3.67	
15	30	27	25	2.400	1.85 - 2.49	Constant-flow area between spike and shell
		30	--	1.810	1.45 - 2.17	
				2.100	1.85 - 2.64	Concentric spike and shell
				2.400	1.81 - 2.49	
				2.700	1.85 - 2.49	



(a) Clustered nozzles in second-throat exhaust diffuser.

Figure 1. - Experimental apparatus for clustered-nozzle investigation.



(b) Exploded view of fixed-area-exhaust-diffuser test apparatus.

Figure 1. - Concluded. Experimental apparatus for clustered-nozzle investigation.

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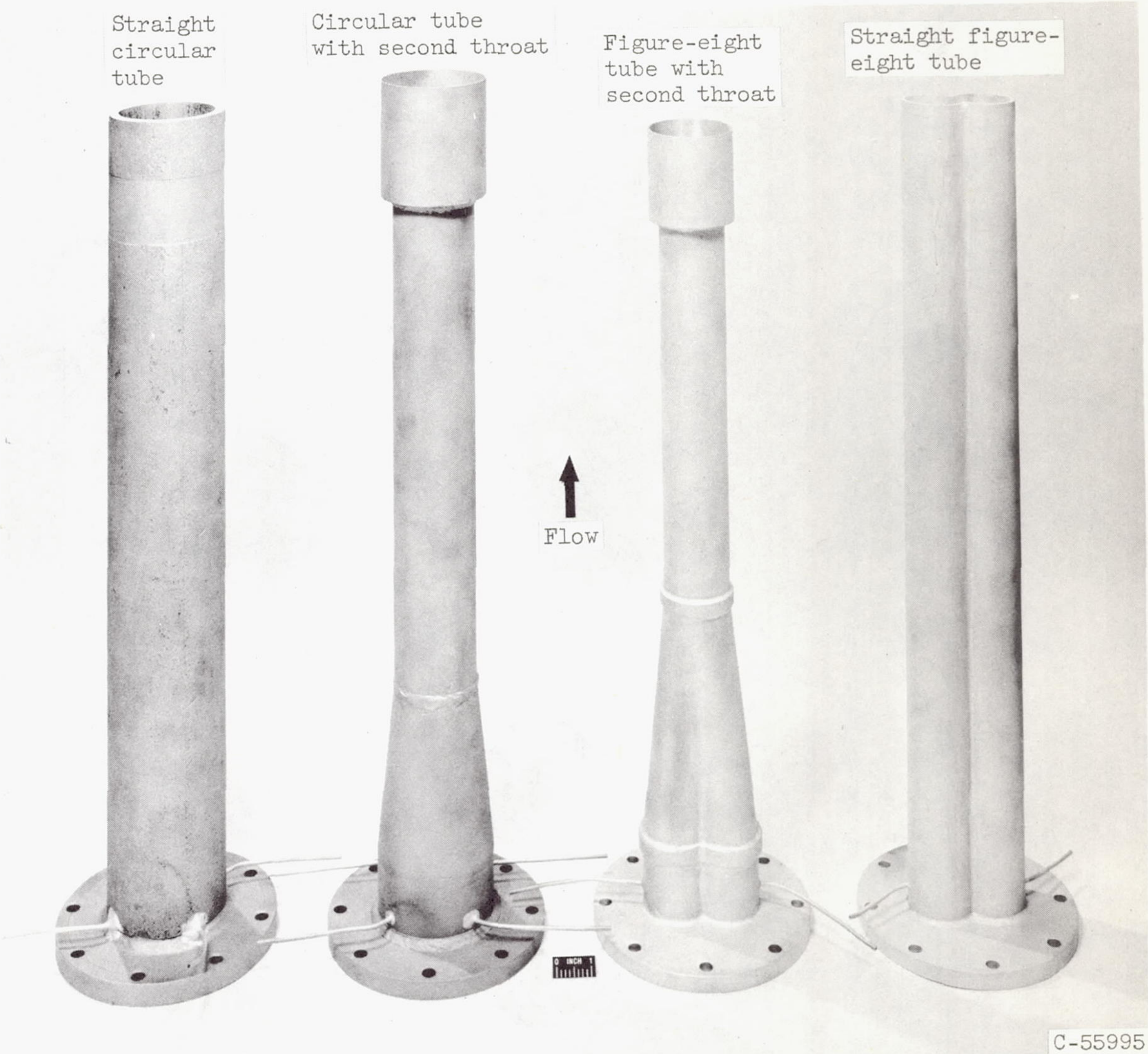

Figure 2. - Fixed-area exhaust diffusers.

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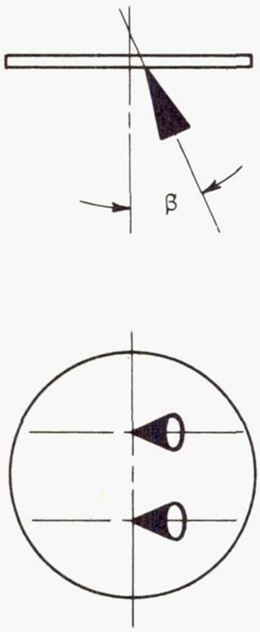
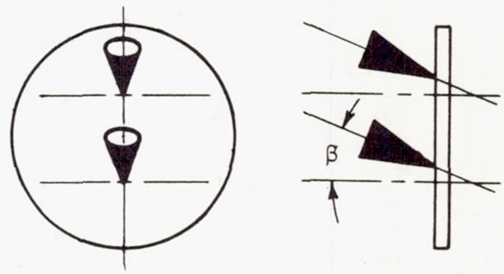
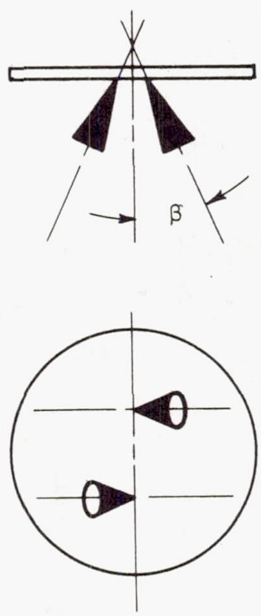


(a) Yaw.



(b) Pitch.



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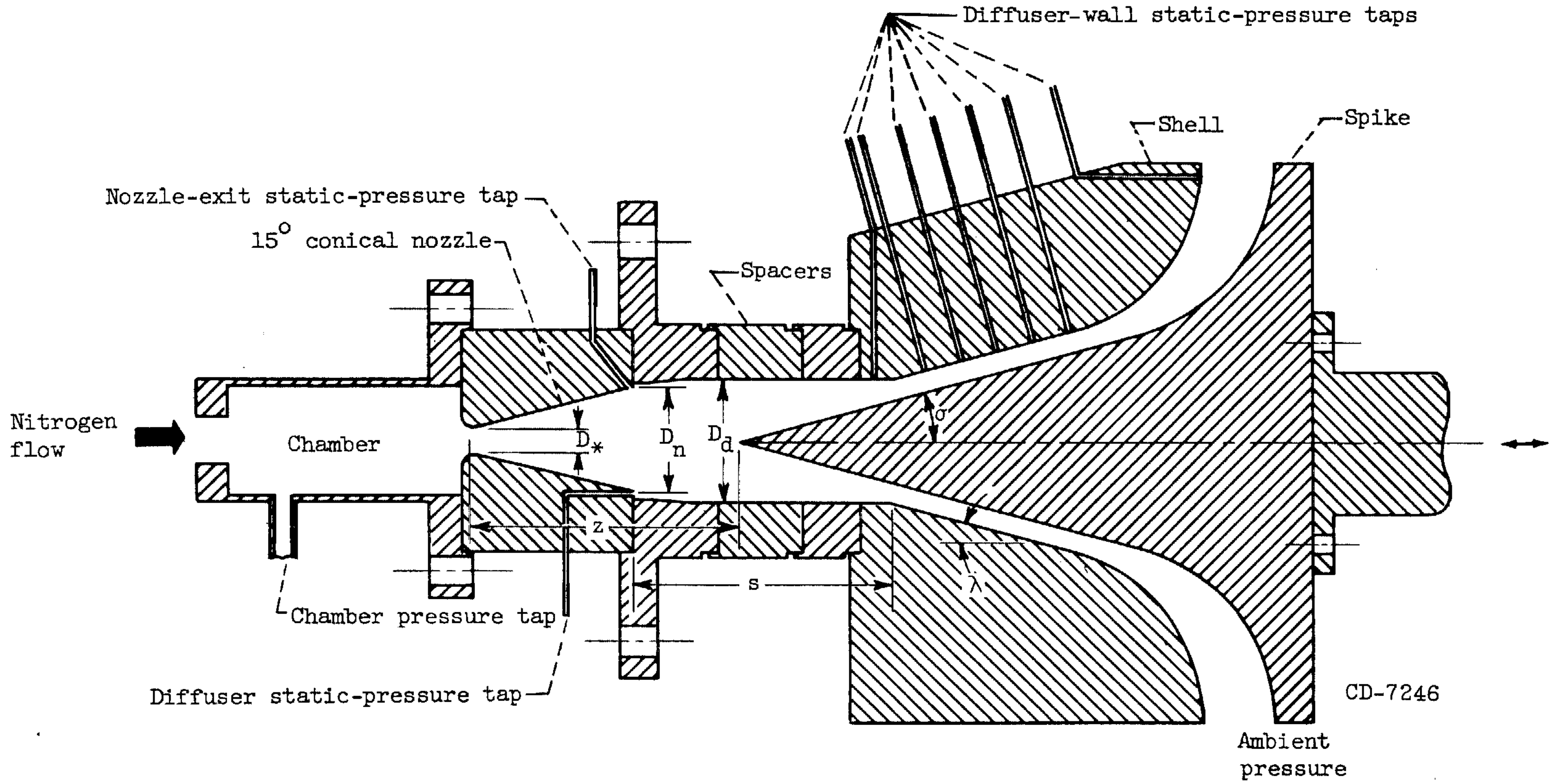
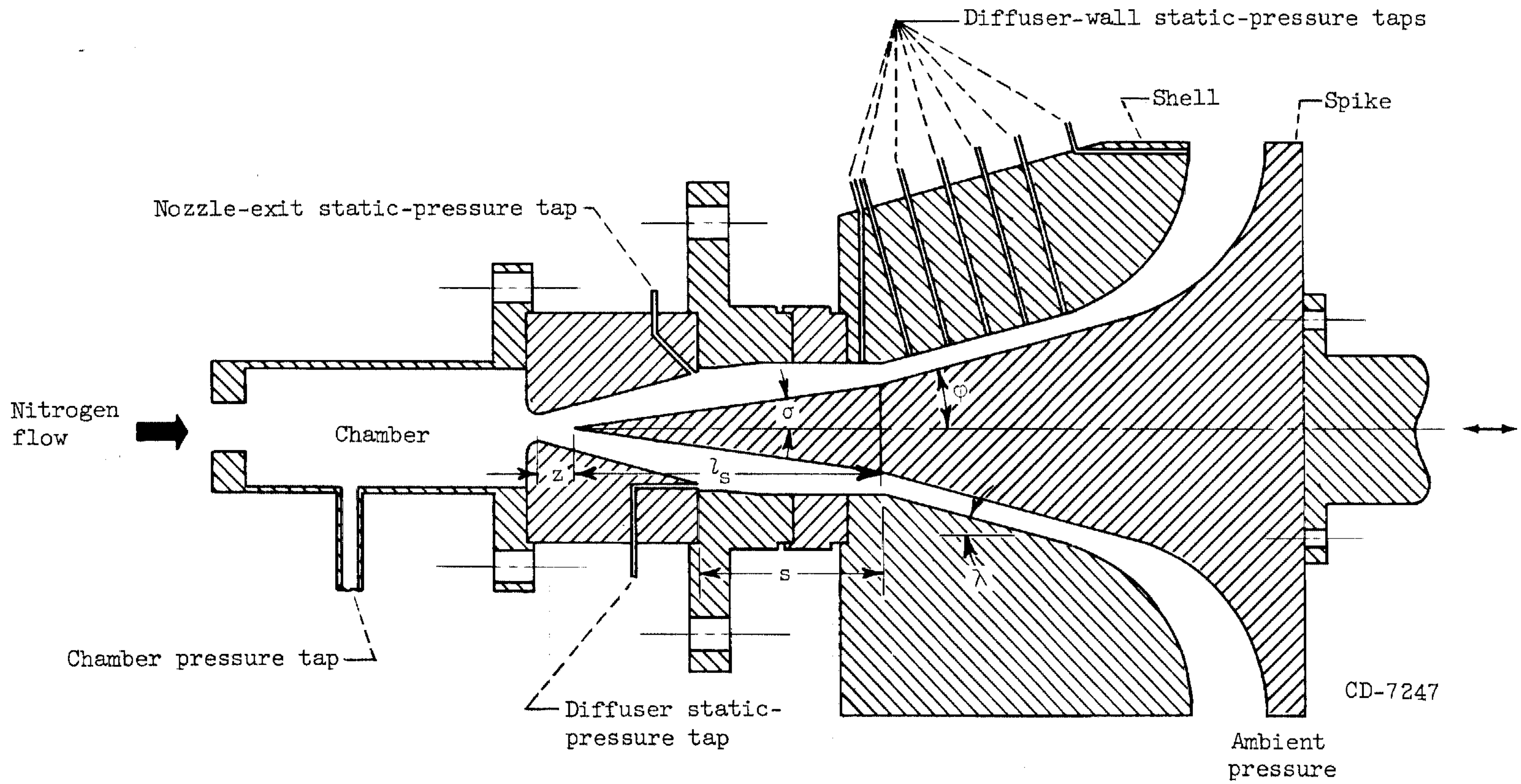
(c) Roll.

Figure 3. - Gimbal attitudes.



(a) Single-step spike.

Figure 4. - Experimental apparatus for variable-area exhaust diffuser.



(b) Two-step spike.

Figure 4. - Concluded. Experimental apparatus for variable-area exhaust diffuser.

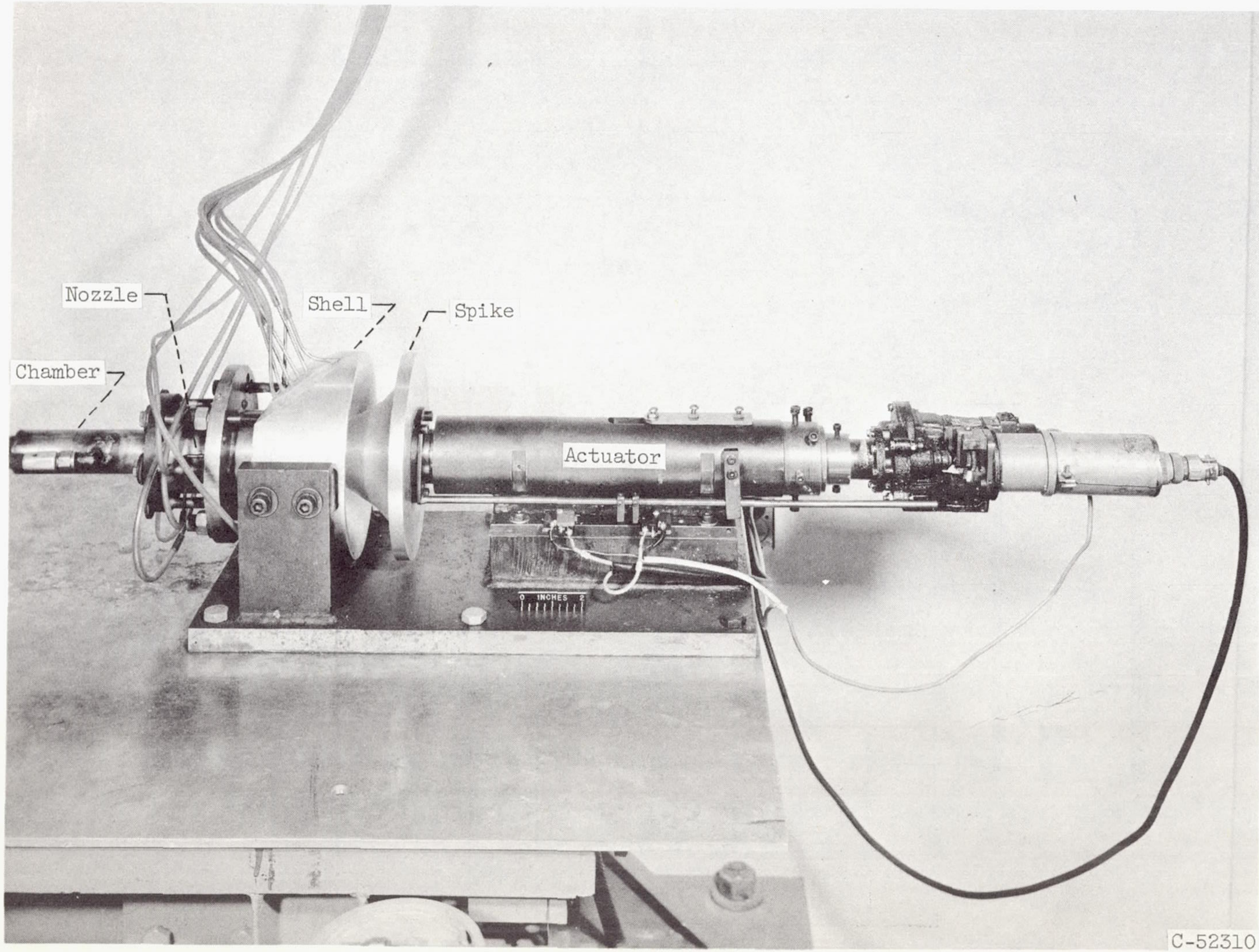
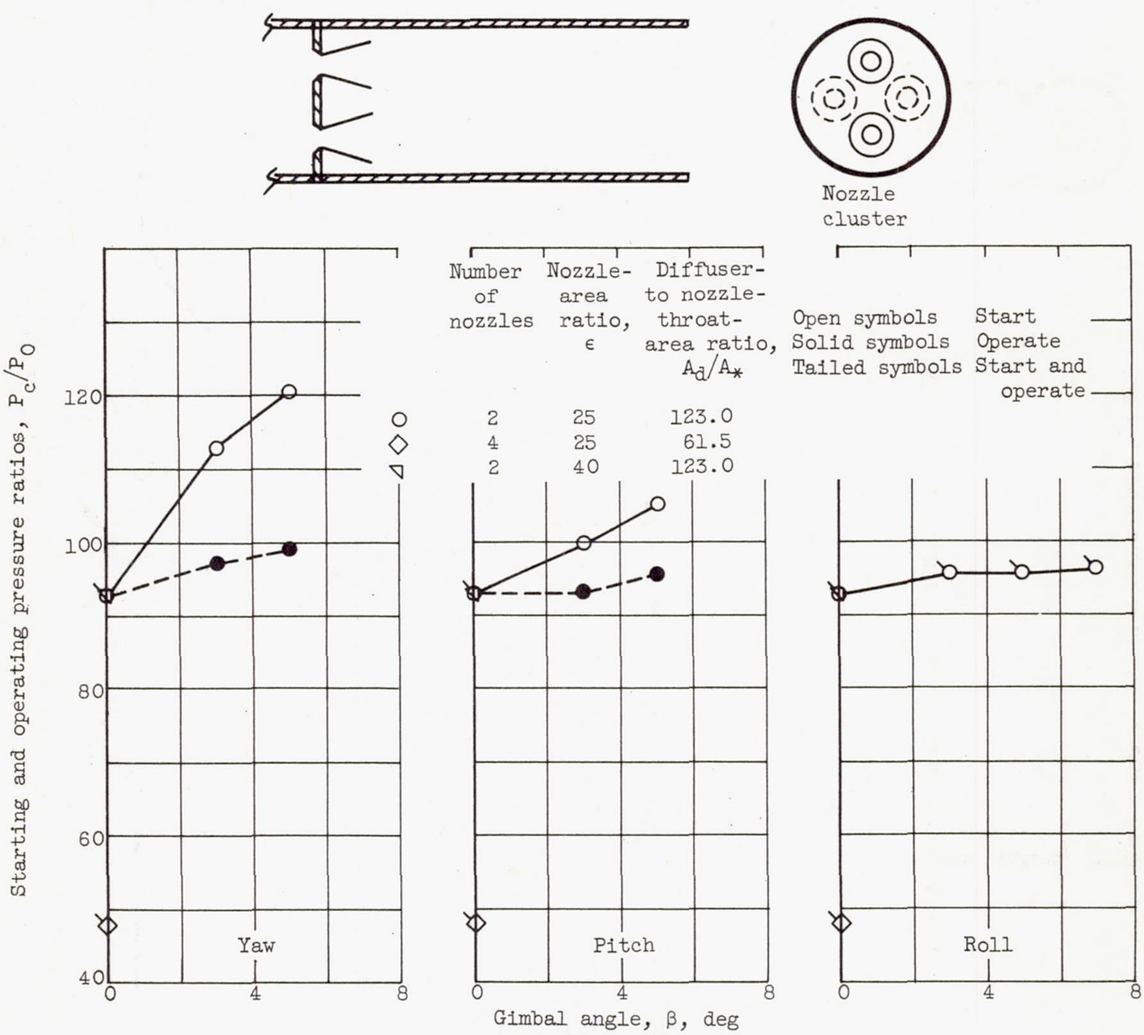
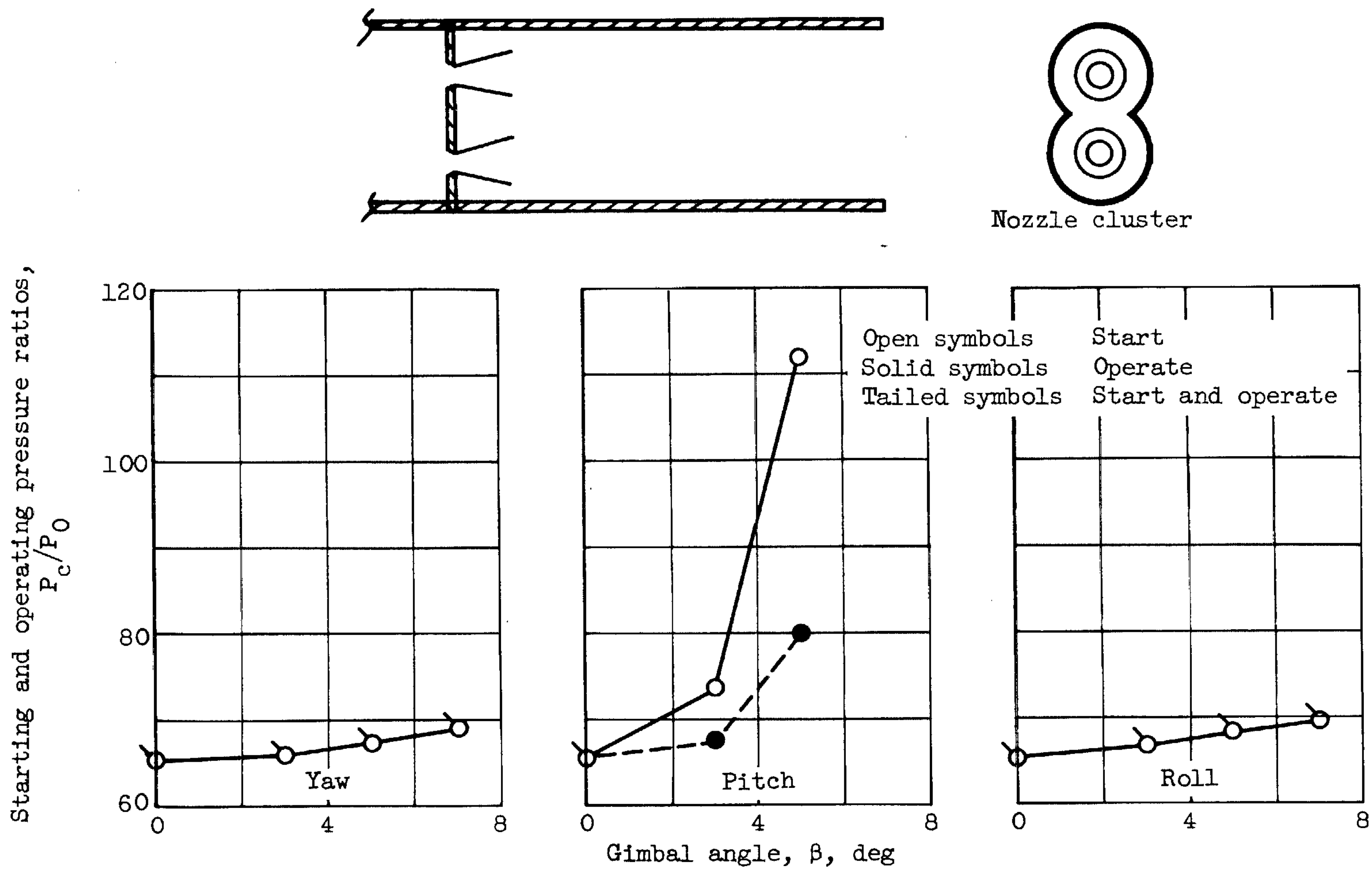


Figure 5. - Variable-area-exhaust-diffuser test apparatus.



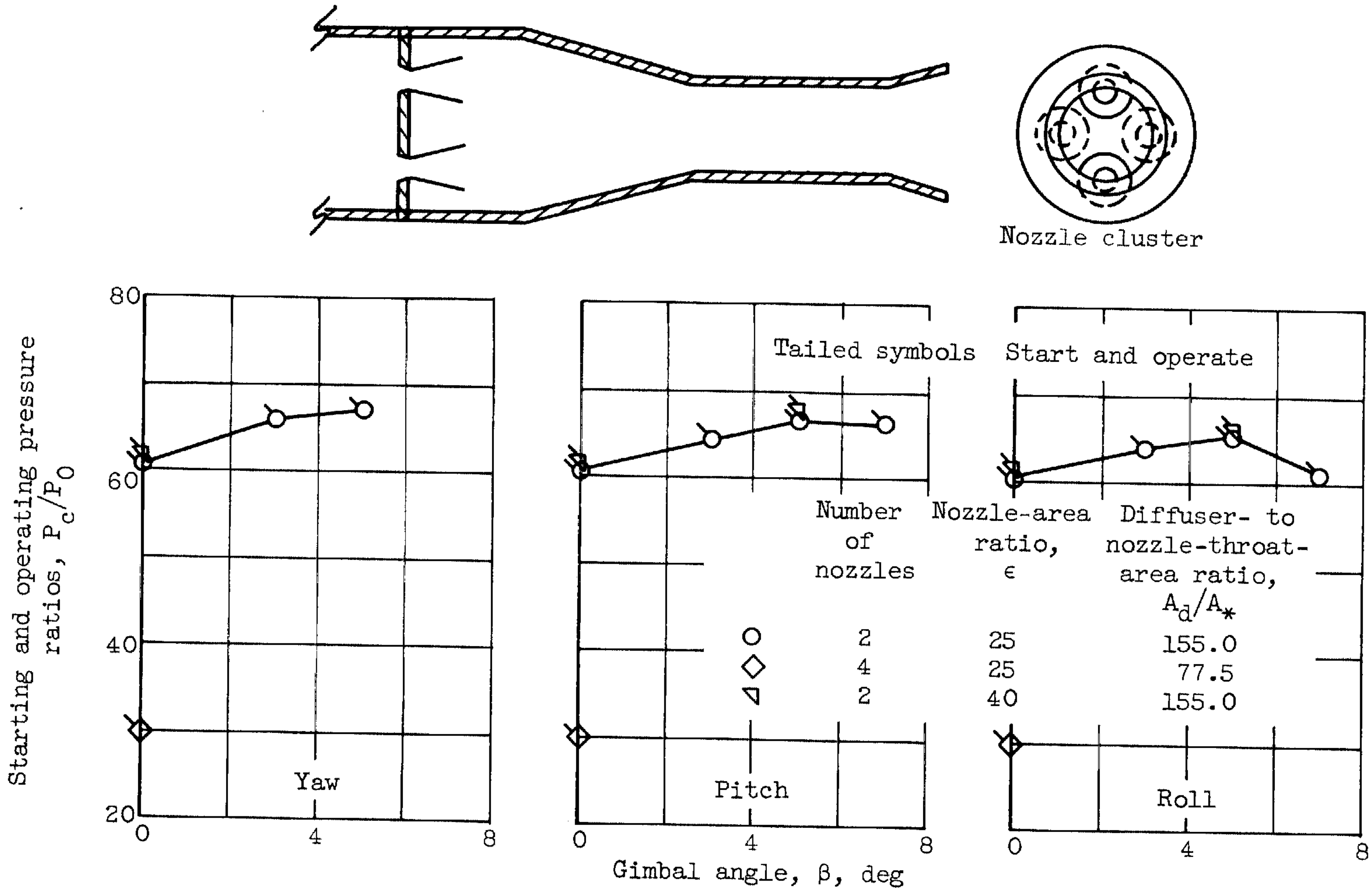
(a) Straight-circular-tube exhaust diffuser.

Figure 6. - Effect of gimbal angle on performance.



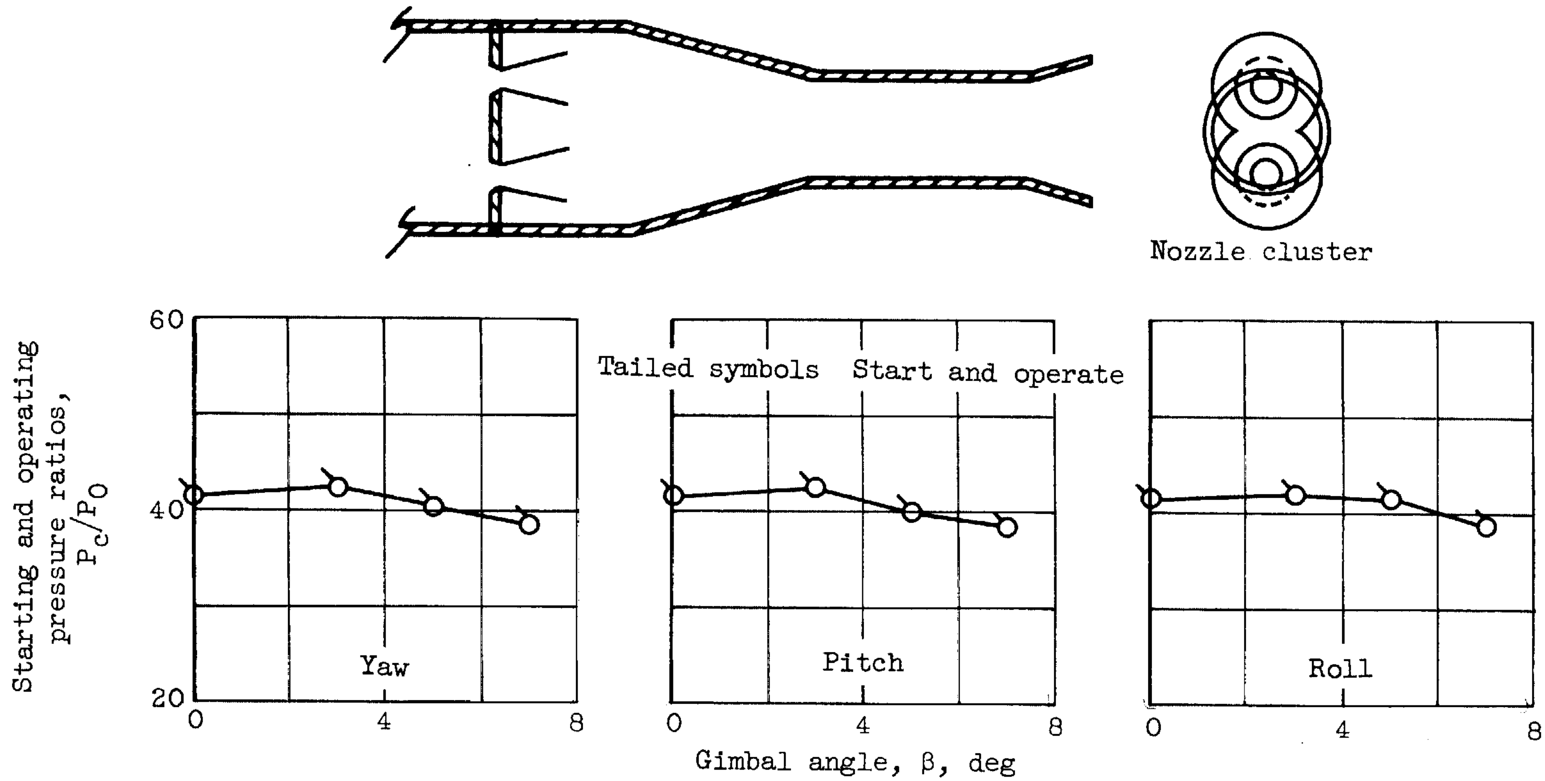
(b) Straight-figure-eight-tube exhaust diffuser with two nozzles with area ratio of 25 and diffuser- to nozzle-throat-area ratio of 87.0.

Figure 6. - Continued. Effect of gimbal angle on performance.



(c) Circular-tube second-throat exhaust diffuser.

Figure 6. - Continued. Effect of gimbal angle on performance.



(d) Figure-eight-tube second-throat exhaust diffuser with two nozzles with area ratio of 25 and diffuser- to nozzle-throat-area ratio of 87.0.

Figure 6. - Concluded. Effect of gimbal angle on performance.

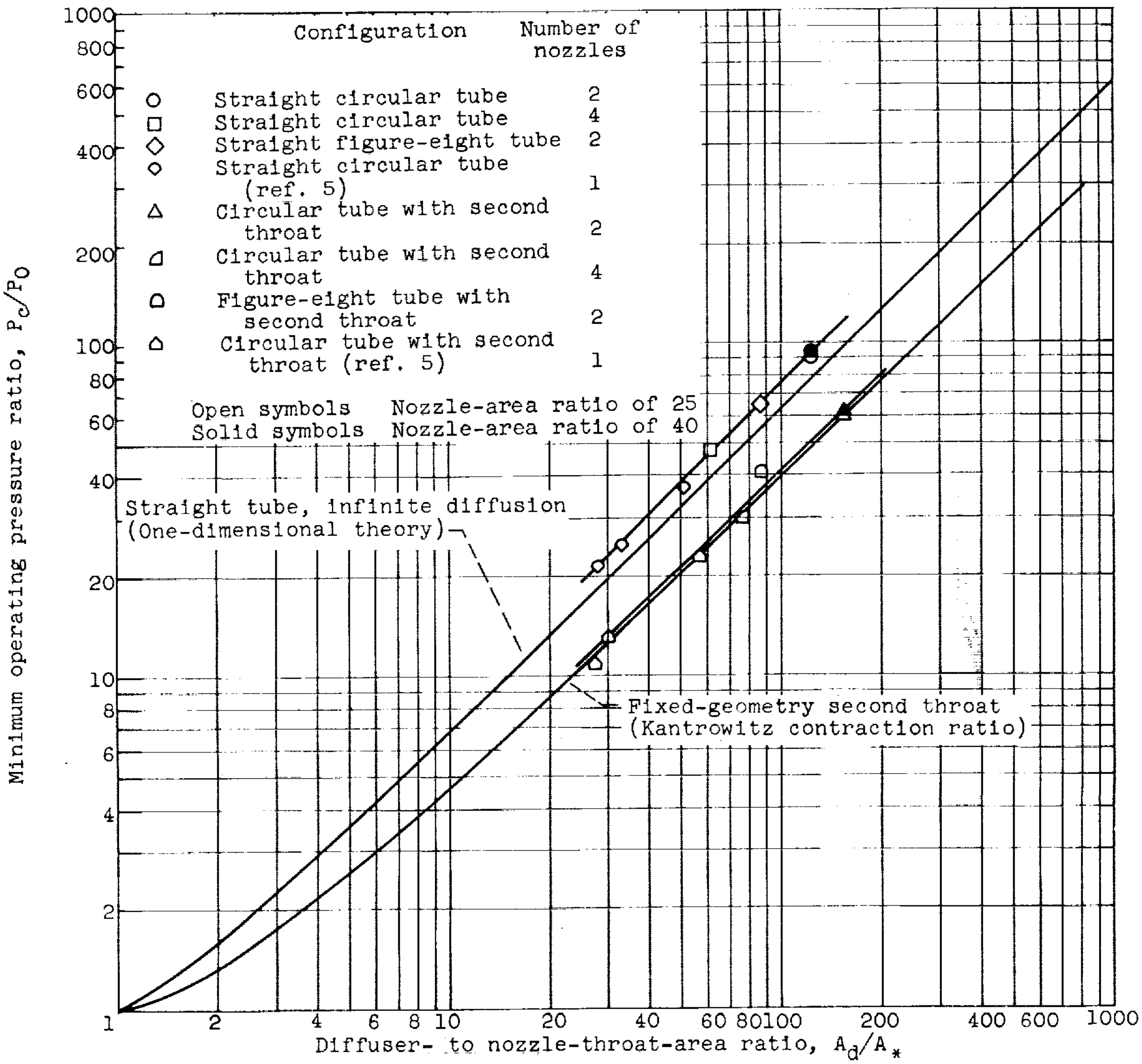


Figure 7. - Effect of diffuser- to nozzle-throat-area ratio on performance of clustered nozzles with no gimbaling.

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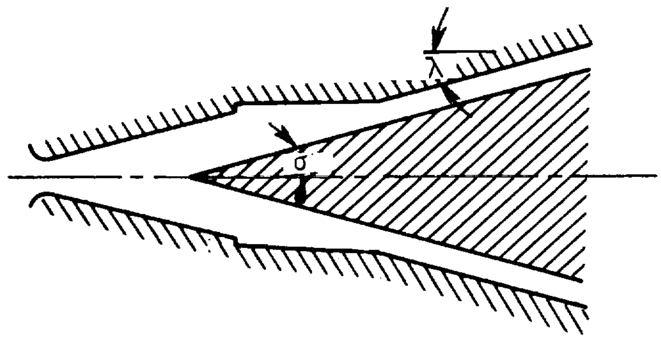

Single-step-spike variable-area exhaust diffuser

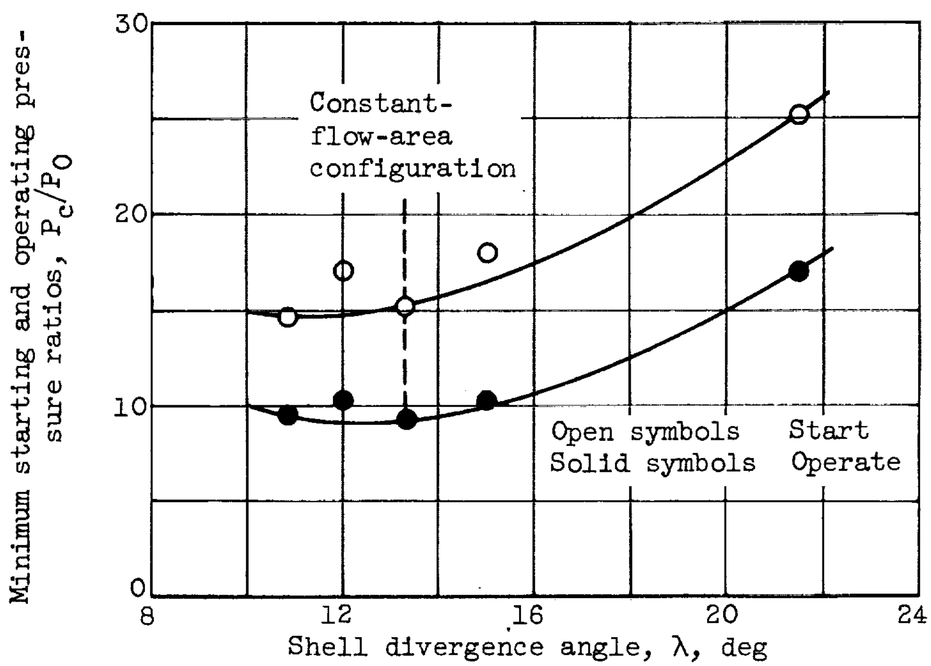

Figure 8. - Effect of shell divergence angle on performance of 15° spike configurations. Diffuser- to nozzle-throat-area ratio, 35.4.

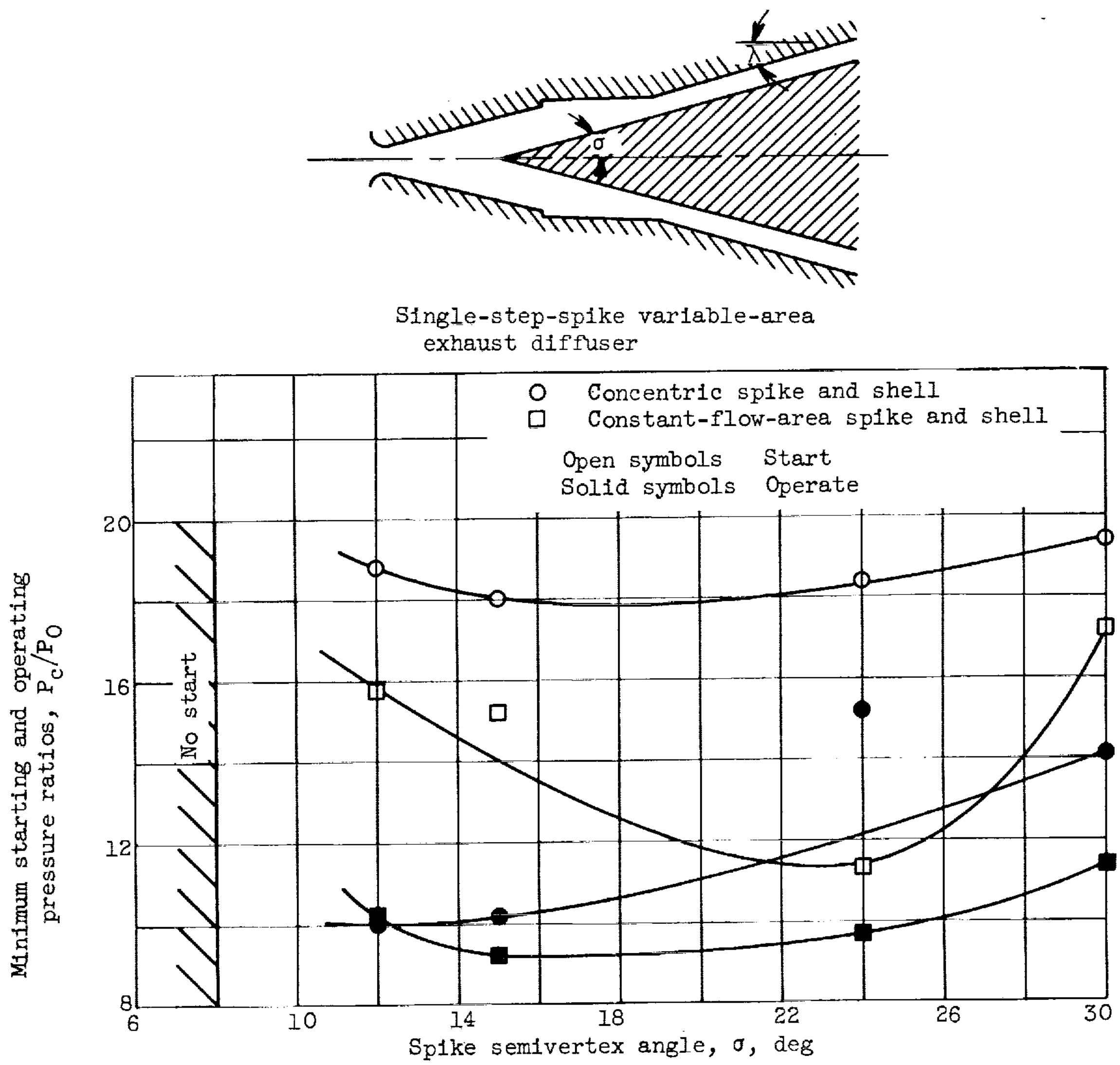

Figure 9. - Effect of spike semivertex angle on performance of concentric and constant-flow-area configurations. Diffuser- to nozzle-throat-area ratio, 35.4.

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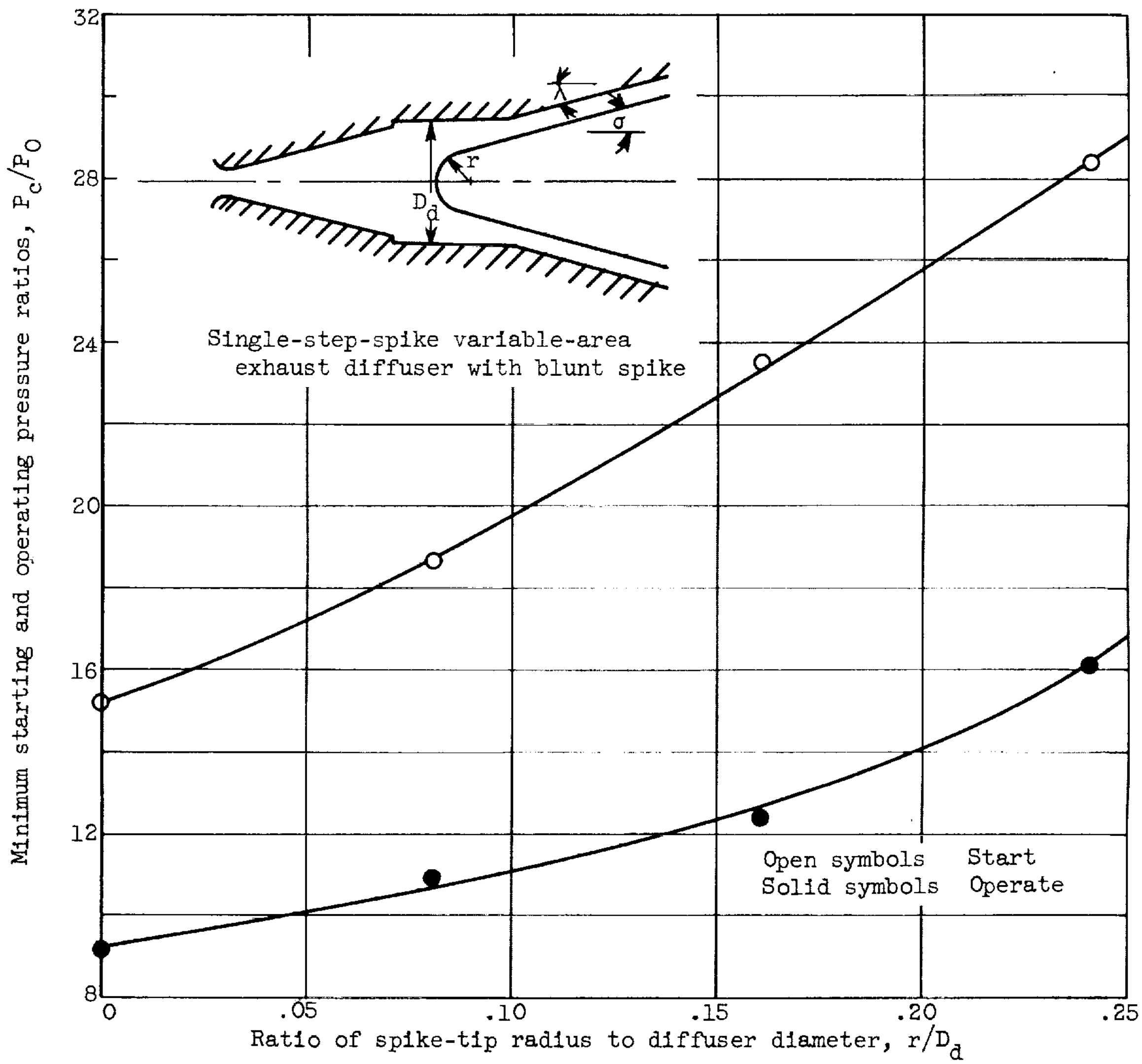

Figure 10. - Effect of spike-tip radius on performance of 15° spike, concentric-flow-area configuration. Diffuser- to nozzle-throat-area ratio, 35.4.

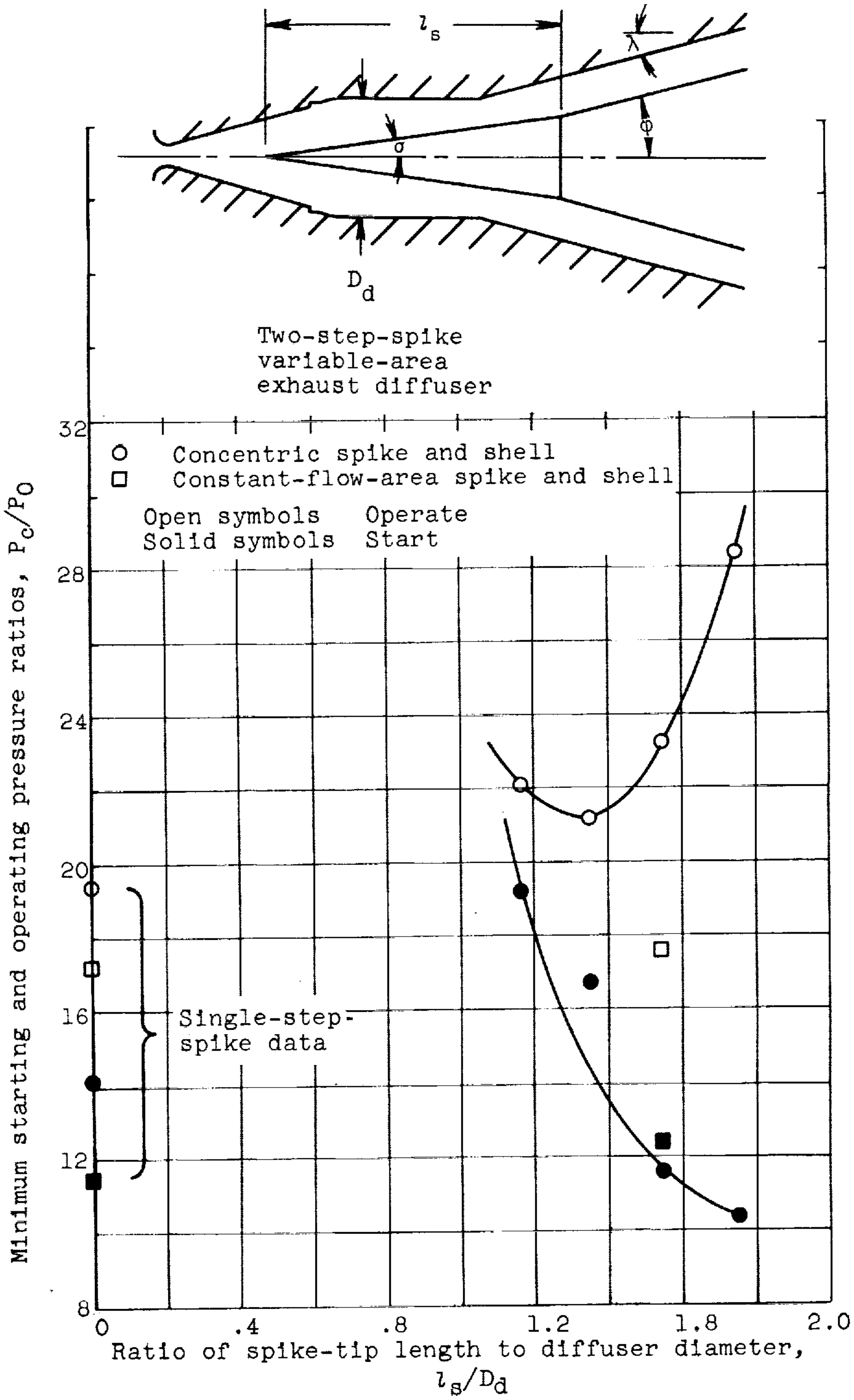

Figure 11. - Effect of spike-tip length on performance of two-step spike. Spike-tip semivertex angle, 15°; spike-base semivertex angle (for two-step spikes), 30°; shell divergence angle, 30°; diffuser- to nozzle-throat-area ratio, 35.4.

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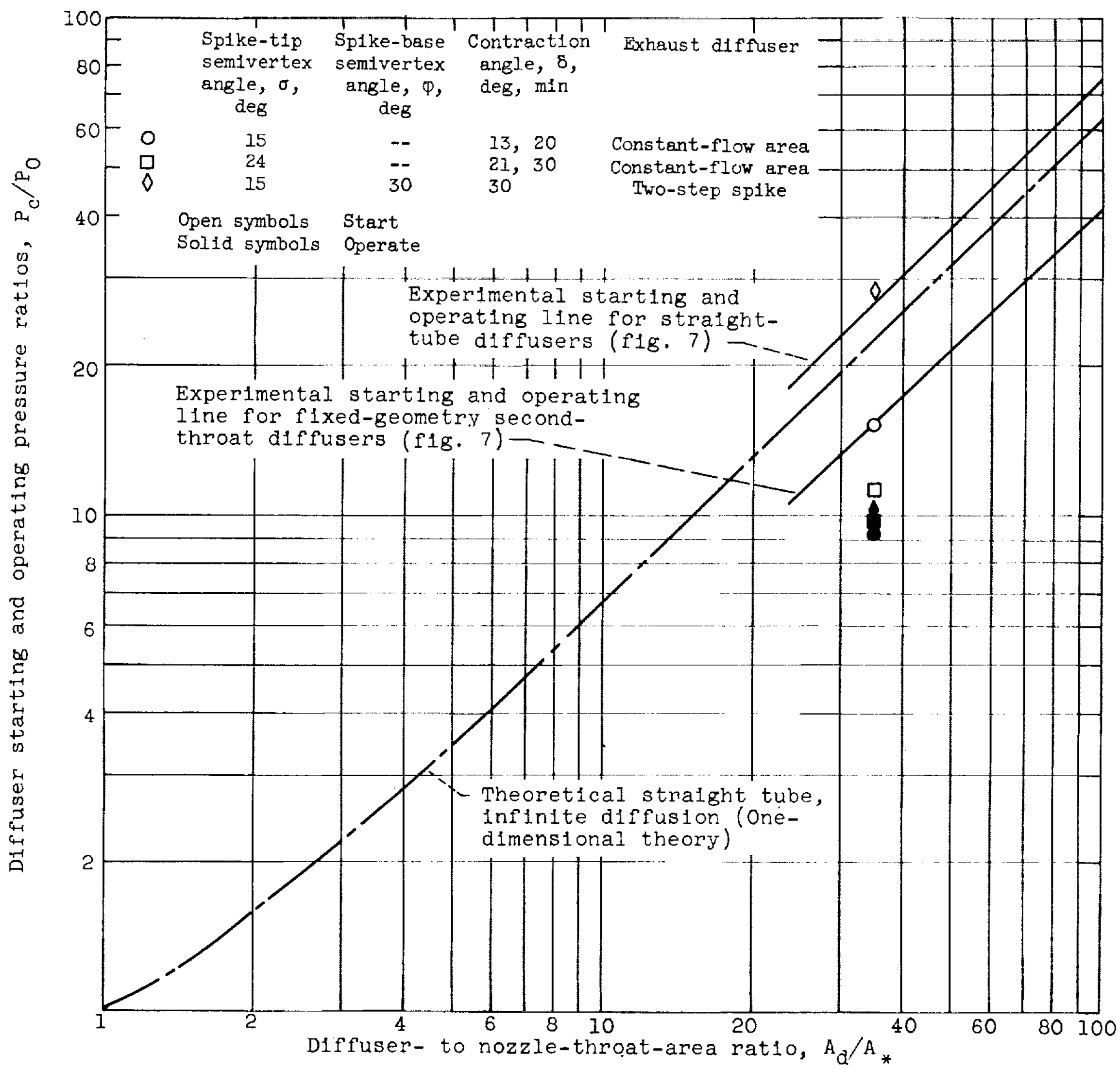

Figure 12. - Effect of diffuser- to nozzle-throat-area ratio on performance of variable-area exhaust diffusers.

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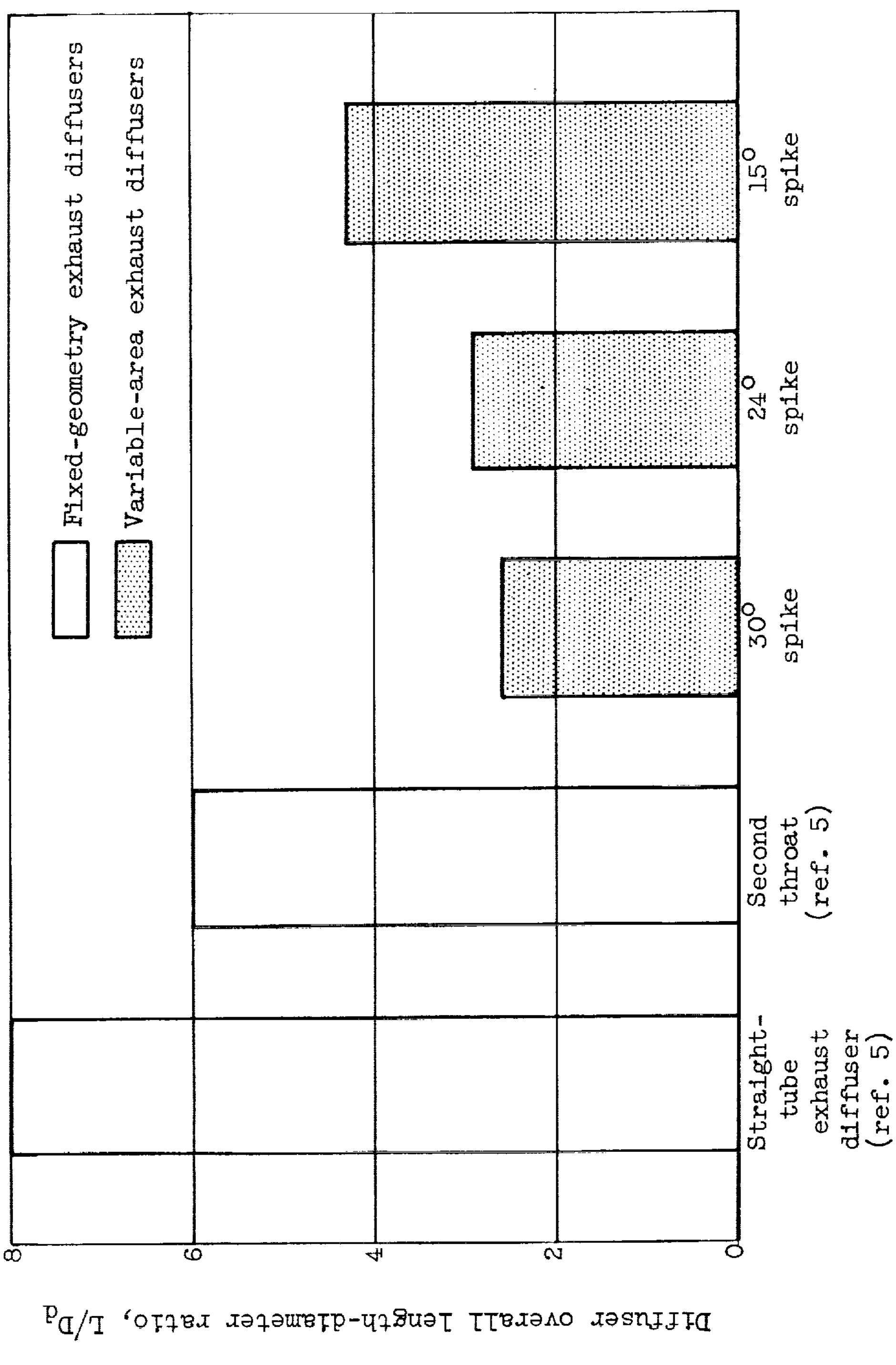

Figure 13. - Overall length-diameter comparison for various types of exhaust diffusers.